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Keywords

Air mobility planning, Aircraft selection modeling, Analysis of alternatives

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ORIGINAL RESEARCH

Aircraft selection modeling: a multi-step heuristic to enumerate airlift alternatives

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Abstract We consider the use of the new C-130J-30 aircraft for long distance (strategic) cargo movement. Currently, only large aircraft, the C-5 and the C-17, are identified as strategic airlift assets by the United States Air Force. Our mathematical model identifies all logical airframe combinations to perform a cargo movement given a set of constraints. Using previously developed routing algorithms and fuel metrics, we evaluated the combinations and calculated the potential savings had the most fuel efficient combination been selected. Analyzing 1 month of historic data for four long distance routes, our proposed model suggests that savings could have been more than one million dollars.

Keywords Air mobility planning · Aircraft selection modeling · Analysis of alternatives

1 Introduction

Unlike the private sector where the profit motive encourages airlines to maximize the utilization of resources (Bayliss et al. 2017; Lau et al. 2009), in the public sector, limited resources necessitate the careful balance of effectiveness and efficiency. Although the motives may differ, the objective of maximizing available resources is the same. One example within the public sector is the airlift mission of the United States Air Force (USAF). The airlift mission is vitally important to accomplishing political, military, and humanitarian objectives; consequently, effectiveness is highly valued and the need to operate the fleet efficiently is certainly desired, but not always emphasized.

USAF airlift planners task and track approximately 900 cargo movements (either strategic or tactical) per day. Strategic cargo movements are intertheater, which means that cargo is

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transported from one Area of Operations (AOR) to a different AOR. Tactical cargo movements are intratheater, which is entirely within one AOR. This is codified in USAF doctrine, which describes air mobility movements as either intratheater or intertheater in nature (United States Air Force 2014a).

Rather than a point-to-point delivery method, the USAF uses a hub-and-spoke method that is similar to the civilian aviation industry (Toh and Higgins 1985). The dominant logic is that this method offers the greatest opportunity for the aggregation of cargo thereby increasing efficiency. It reinforces the segregation of USAF aircraft into larger aircraft to support strategic cargo movement between hubs and smaller aircraft to support tactical cargo movement along the spokes. As with operations research in the public sector (Sinuany-Stern and Sherman 2014), the hub-and-spoke model has been around since the advent of air mobility following World War II. Unfortunately, the hub-and-spoke model has remained largely static despite substantial advances in aircraft technology. This presents an opportunity to challenge the current private and public sector hub-and-spoke model by taking a holistic approach to aircraft selection, given a set of validated requirements. Regardless of the designation of the cargo movement as strategic or tactical, all capable airlift assets should be analyzed to increase efficiency while not sacrificing effectiveness.

Hence, the purpose of this study is to assess potential increases in efficiency by considering all capable airlift assets in the planning of air mobility operations. To that end, a mathematical model was developed that accurately enumerates all logical airframe alternatives or combination of airframes to perform a specific airlift operation given a set of user-defined constraints. This model could enable airlift planners to easily generate relevant metrics for comparison including fuel consumption, operating costs, and delivery time. The aircraft selection model (ASM) is a multi-step heuristic algorithm that allows airlift planners to define constraints such as route, available aircraft, cargo requirements, and required payload characteristics such as weight, volume, and outsize cargo (i.e. cargo unable to be loaded to a C-130J-30). In turn, the model's output defines the optimal aircraft mix and payload configuration based upon minimizing the objective function of fuel consumption.

This study analyzes the current USAF mobility airlift planning practice of allocating airlift assets and evaluates if taking a more holistic approach would result in efficiencies. Therefore, the stated research question is: how much, if any, operational cost and/or fuel savings can be realized by using a holistic approach to strategic airlift? The remainder of the paper is organized as follows. First, we review relevant literature. Next, we describe the methodology used in this study and explain the analysis. Finally, we discuss the findings and conclusions.

2 Literature review

This section describes the evolution of the Lockheed C-130 and explains the capability of the mobility aircraft in the USAF inventory. Additionally, we summarize mobility doctrine and discuss the trade-offs associated with hopping (i.e. multiple stops). Finally, we outline costs and fuel metrics used in the analysis of alternatives.

2.1 Evolution and role of the C-130

The latest major upgrade of the C-130 cargo aircraft is the C-130J model. It incorporates state-of-the-art technology that significantly increases range and fuel efficiency while decreasing operational and life-cycle costs. A stretch-version of the aircraft, the C-130J-30, was produced with 15 extra feet of fuselage extending its payload capacity by 33%. Table 1 shows a

Table 1 Mobility aircraft comparison

	 C-130J-30*	 C-17A*^	 C-5A/B/C*	 C-5M^
Speed	410 MPH	450 MPH	518 MPH	586 MPH
Max payload	44,000 lbs	170,900 lbs	270,000 lbs	285,000 lbs
Range (unrefueled)	2100 NM	2400 NM	4350 NM	5250 NM
Pallet positions	8	18	36	36

MPH miles per hour, *NM* nautical miles
*US Air Force MDS Fact Sheets; ^Manufacturer's specifications

comparison of USAF mobility aircraft. When not considering the total cost, it is clear that the C-17A and C-5 aircraft possess distinct advantages with regard to speed, payload, and range over the C-130J-30 (United States Air Force 2014b, 2015c).

USAF doctrine describes intertheater operations as airlift between two or more AORs, while intratheater operations is airlift exclusively within one AOR (United States Air Force 2014a). The C-17A and C-5 aircraft with their larger capacity and greater range are generally designated intertheater airlift, and C-130 aircraft are commonly assigned under the direct control of an AOR commander.

In the civilian sector, regional aircraft are playing an increasingly important role in the growth of the airline industry in the US, which allows for expanded hub operations and the opening of new markets. Likewise, in the USAF, C-130 aircraft fill the same vital role. With the C-130's direct delivery capability and recent upgrades, there are unique opportunities to explore and possibly exploit this aircraft beyond their simple application as an intratheater asset (Cook 1998).

2.2 Increased efficiency through hopping

By considering smaller aircraft for strategic cargo movement, planners must account for the limited fuel capacity and the need to stop and refuel more often (Gabteni and Grönkvist 2009). These stops incur additional fuel costs and increase the delivery time; however, smaller more frequent cargo movements may generate faster overall delivery times.

With cruise speeds for conventional aircraft designs plateauing, engineers have begun to build larger aircraft with greater payload capacity to enable productivity increases (Nangia 2006). The unfortunate side-effect of this approach is that exceedingly large aircraft pay a stiff penalty in fuel consumption and efficiency. Work by Green (2005) and Nangia (2006) have shown that, using today's technology, the most payload/fuel efficient passenger aircraft design is optimized at a range of approximately 3000 nautical miles (Green 2005). Green hypothesized that fuel savings could be realized by using in-flight refueling or segregating considerably long routes into a number of smaller legs (2005). Similar analysis by Hahn (2007) builds upon their work and showed that in a commercial passenger setting, a conservative estimate of fuel savings of approximately 29% can be achieved by breaking up longer routes of 15,000 km into three stages of 5000 km each and redesigning aircraft for this specific type of operation (Hahn 2007). While these studies have been primarily applied to commercial passenger airlift, the principle should be explored within the context of military cargo airlift operations.

Using a fuel efficiency metric that considers payload throughput, Reiman (2014) calculated that maximum efficiency for the C-17A peaked at between 1000 and 2000 nautical miles. His analysis highlighted the trade-offs that must be made between payload, range, and fuel. Lapp and Wilkenhauser (2012) minimized the amount of fuel used given a set of tails and a set of the lines of flight. Our technique called these lines of flight a route. Our approach avoids fixing lines of flight and calculates the line of flight for optimal cargo throughput. Transload operations were avoided in this analysis due to the negative impact of the additional ground time on cargo throughput. Our approach also uses actual cargo loading allowing for greater accuracy of aircraft payloads and more thorough analysis over multiple metrics including fuel, cost and time. According to results by Reiman, a C-17A travelling 4000 nautical miles can carry 64,000 lb of cargo, but segmenting that same cargo movement into two 2000 nautical mile sorties more than doubles available cargo capacity to 143,000 lb (Maywald 2016). The inherent trade-offs are represented in Table 2 which lists the capabilities of the various aircraft for the Dover, Delaware to Ramstein, Germany route.

As shown in Table 2, making an additional stop can significantly increase the maximum allowable payload and weight per pallet allowed. As an illustration, the different possibilities of moving 230,000 lb of cargo from Dover to Ramstein. With no stops, the weight constraint of this payload would necessitate using multiple aircraft. However, assuming the volume constraint would allow for its loading, a single C-5M could theoretically deliver this payload to its final destination by adding just one stop enroute to its final destination.

2.3 Costs by aircraft type

There are several metrics used by the USAF to track and assess the cost of operating the different aircraft in its mobility fleet. This next section will briefly describe these metrics, how they are applied to the various aircraft, and how they are useful for comparison in our analysis.

2.3.1 Total ownership costs

The air force total ownership costs (AFTOC) system is a database that makes available an aggregated, single authoritative source of financial and logistics data to USAF cost analysts. AFTOC provides a single, comprehensive cost per flying hour (CPFH) for each aircraft type. This provides useful insight beyond the simple variable costs associated with operating the airframes and provides a glimpse into the true cost of operating the aircraft (United States Air Force 2015a). The actual AFTOC costs are not publicly releasable; however, we may address them in relative terms. As a percentage of C-17A AFTOC costs, the C-130J-30 is 34%, the C-5B is 228%, and the C-5M is 152%.

2.3.2 Logistics costs

Air force instruction 65–503 uses AFTOC source data to calculate semi-variable logistics cost planning factors by flying hour and primary aircraft authorizations. It contains official USAF cost and planning factors that activities use to estimate resource requirements and costs associated with structures, missions, and activities. The calculations include supplies, fuel, as well as logistics support maintenance and repair associated with each aircraft type. Again, the actual logistics costs are not publicly releasable. As a percentage of C-17A logistics costs, the C-130J-30 is 30%, the C-5B is 166%, and the C-5M is 113%.

Table 2 Stop/performance tradeoffs

	C-130J-30		C-17A		C-5B		C-5M	
	Max payload	Weight/pallet allowed	Max payload	Weight/pallet allowed	Max payload	Weight/pallet allowed	Max payload	Weight/pallet allowed
0	N/A		85.3	4.7	123.4	3.4	179.1	4.9
1	42.9	5.3	142.3	7.9	177.8	4.9	232.0	6.4
2	53.0	6.6	156.7	8.7	234.4	6.5	270.0	7.5

All weights are in 100,000 lb and truncated to the first decimal place

2.3.3 *Cost to the customer*

The USAF uses those metrics in calculating the Special Assignment Airlift Mission (SAAM) rate, which is what the USAF charges all airlift customers per flying hour. An aircraft's allowable cabin load (ACL) and speed are multiplied to form a metric called the ton mile factor (TMF). For example, the C-130J-30 has an ACL of 15.8 and a speed 308 MPH. Thus, the TMF for the C-130J-30 is 4866. For each aircraft type the TMF is multiplied by either the strategic revenue per ton mile factor ($1.18 for the C-17A) or the much higher tactical revenue per ton mile factor ($3.06 for the C-130J-30).

The revenue per ton mile metric, which is calculated by surveying the civilian airline industry's long-range and short-range operational costs, obscures the SAAM rates in relation to the capability that a particular aircraft type can deliver. The SAAM rate for the C-130J-30 is $14,908 per hour, C-17A is $16,379 per hour, and for both the C-5B and C-5M it is $35,899. To airlift customers, clearly the C-17A delivers far greater cargo movement capability for the price, especially if the unit is exceeding the cargo capacity of a single C-130J-30. This creates a disincentive to use the smaller aircraft for any kind of long-haul move, despite the possibility of actual cost savings to the USAF in the operation of the smaller aircraft. However, if the C-130J-30 SAAM rate was calculated using the strategic revenue per ton mile factor, the new C-130J-30 SAAM rate would be a much more competitive, $5741 per hour. Similarly, if the C-17A SAAM rate were calculated using the tactical revenue per ton mile factor, its new SAAM rate would be $42,604 per hour. While the C-130J-30's calculated speed is about 21% slower than the C-17A (which means more flying time), changing the rate calculations to remove the artificial disparity between strategic and tactical assets should prove to be a strong incentive for customers to choose the most efficient option.

2.4 Fuel costs

The Defense Logistics Agency–Energy is the single provider for all USAF aviation fuel. The standard price of aviation fuel is generally only published once or twice each year, which insulates the military services from the normal ups and downs of the fuel marketplace (DLA Energy 2016). Relative to logistics factors, aviation fuel accounts for between 50 and 70% of flying hour costs and therefore volatility in the price of fuel is a major contributor to variability in overall expenditures.

3 Methodology

This section contains an overview of the model, the data collected, and the design of this analysis. First, the development of the multi-step heuristic algorithm which is necessary in the aircraft selection model is discussed. Next, how the data were collected is described. Lastly, the design of the analysis is described and the major assumptions are outlined.

3.1 Aircraft selection model

We developed the aircraft selection model (ASM) to enumerate the entire decision space so that an objective aircraft selection choice could be made. While the ASM can be modified to model different objective functions, our model minimizes fuel consumption. To create the ASM, a multi-step heuristic was applied to satisfy variations of two common complex problems (i.e. aircraft mix and aircraft loading). The first step requires the complete enumeration of the set of aircraft alternatives for a given set of requirements. The second step attempts to efficiently allocate the specified payload to each aircraft in each alternative. After the model enumerates alternatives and allocates the required cargo, the third step computes metrics for each alternative based on aircraft type, routing, and payload. Additionally, each alternative is ranked based on minimum fuel consumption. ASM was coded into hypertext markup language (HTML) format using JavaScript, which provides a straightforward user-interface and allows input and output information to be easily shared and understood. The pseudo code of enumeration of alternatives and aircraft loading are given below.

Algorithm 1 Enumeration of alternatives

```
Calculate max number of C-5Bs by dividing total cargo pallet position equivalent (PPE) by 36
  pallet positions
Calculate max number of C-5Bs based on dividing total cargo weight by C-5B max weight
Take the larger of max number of C-5Bs by weight or cube
for C-5Bs from the max number down to zero do
    Calculate C-5B PPE remaining after 36 times the number of C-5Bs are loaded
    Calculate C-5B cargo weight remaining after loading to max weight times number of C-
5Bs
    Calculate max C-5Ms based on dividing total cargo PPE remaining by 36 pallet positions
    Calculate max C-5Ms based on dividing total cargo weight remaining by C-5M max
weight
    Take the larger of max number of C-5Ms by weight or cube
    for C-5Ms from the max number down to zero do
        Calculate PPE remaining after 36 times the number of C-5Ms are loaded
        Calculate cargo weight remaining after loading to max weight times number of C-5Ms
        Calculate max C-17As based on dividing total cargo PPE remaining by 18 pallet
          positions
        Calculate max C-17As based on dividing total cargo weight remaining by C-5M max
          weight
        Take the larger of max number of C-17As by weight or cube
        for C-17As from the max number down to zero do
            Calculate PPE remaining after 18 times the number of C-17As are loaded
            Calculate cargo weight remaining after loading to max weight times number of C-
                17As
            Calculate max C-130J-30s by dividing min of remaining PPE or non-outsize PPE
              by 8 pallet positions
            Calculate max C-130J-30s by dividing min of remaining weight or non-outsize wt
              by max C-130 wt
            Take the larger of max number of C-130J-30s by weight or cube
            if no C-5Bs, C-5Ms, C-17As and outsize cargo exists then
                C-130J-30s are not viable
            end if
            Build specific aircraft arrays for C-5B, C-5M, C-17A and C-130J-30 alternatives
            Add Fleet Mix Alternative from specific aircraft arrays
        end for
    end for
end for
```

Algorithm 2 Aircraft loading

```
for each fleet mix alternatives do
    Sort cargo array by weight descending
    while cargo array length > 0
        for each MDS type in the alternative do
            for each aircraft for the MDS type in the alternative do
                if next cargo item does not exceed weight or PPE limits then
                    Add cargo to the aircraft
                    Compute aircraft cargo weight with cargo added
                    Compute aircraft PPE with cargo added
                    Compute aircraft cargo load factor by weight
                    Compute aircraft cargo load factor by PPE
                    Compute MAX of load factor by weight or load factor by PPE
                    Determine if this aircraft has the MIN of the MAX load factors from all
                    previous aircraft in the fleet mix alternative
                end if
            end for
        end for
        for each MDS type in the alternative do
            for each aircraft for the MDS type in the alternative do
                if not the aircraft with MIN of the MAX load factors then
                    Remove cargo from the aircraft
                    Remove added cargo weight from aircraft cargo weight
                    Remove added cargo PPE from aircraft PPE
                end if
            end for
        end for
        Remove cargo from cargo array
    end while
end for
```

The enumeration of all aircraft mix alternatives is based upon two components. The first is the PPE available for a specific mission design series (MDS) aircraft type. The second is the cargo weight that the aircraft could carry given an origin and destination city pair and the Reiman (2014) calculated cargo throughput maximized routing. The loading of cargo onto aircraft starts with the heaviest cargo item and loads that item onto all of the aircraft in an alternative. The aircraft with the minimum load factor after the item has been loaded will load the cargo item. The load factor used is specified as the maximum of the load factor by weight or load factor by cube. Finally, the calculation of metrics to sort alternatives is based on fuel consumption, time, and cost.

The tail assignment problem has many sub-problems associated with it. The sub-problems include aircraft enumeration, routing determination, max payload calculation, cargo loading and aircraft performance assessment. These sub-problems require inputs including the set of cargo requirements, the set of available aircraft to move those requirements, and the set of airfields that could be traversed. Aircraft enumeration consists of defining all aircraft mix alternatives based upon the actual aircraft capabilities for a given cargo throughput optimized route. The cargo throughput optimized route was determined using the algorithm developed by Reiman (2014). Given that specific route, the max payload for each aircraft was calculated using the max gross takeoff weight available at the origin airfield and the ramp fuel required. Cargo loading assigned each unit of cargo to all aircraft in an alternative and then determined the impact on load factors. The aircraft with the least impact to load factor received that unit of cargo. The unit of cargo was removed from all other aircraft and then the process was reiterated until all cargo was assigned to all the tails in that alternative. With each aircraft, route and payload determined, the metrics for each routing alternative could be assessed. Upon user selection of the desired metric, the optimal aircraft mix alternative was selected.

3.1.1 Aircraft enumeration

A logic-based heuristic was developed and coded as a looping algorithm (see Eq. 1).

$$\gamma_{\mathrm{i}} = \mathrm{ROUNDUP}\left(\mathrm{MAX}\left(\frac{\theta_{\mathrm{total}}}{\theta_{\mathrm{i_{max}}}}, \frac{\sigma_{\mathrm{total}}}{\sigma_{\mathrm{i_{max}}}}\right)\right) \forall \mathrm{i} \tag{1}$$

where

γ_{i}	Maximum number of aircraft required of aircraft type *i* to deliver all cargo
i	Aircraft mission design series (MDS)—type
θ_{total}	Total number of cargo requirements in PPE
$\theta_{\mathrm{i_{max}}}$	PPE constraint for aircraft type *i*
σ_{total}	Total cargo weight requirements in thousands of pounds (Klbs)
$\sigma_{\mathrm{i_{max}}}$	Payload capacity constraint for specific cargo throughput optimized route

The aircraft weight capacity was determined by using the maximum payload weight for the given route that resulted in optimal cargo throughput. A loop is then used to iteratively reduce the number of aircraft within this specific type by one until zero is reached for this aircraft type. During each iteration, another embedded loop calculates the smallest number of necessary aircraft of the next type being analyzed by considering the remaining cargo, and again using the maximum of the PPE or weight ratios and a round-up function. Each of those loops include subordinate loops with the same function for the next aircraft type in the alternative until the function enumerates the maximum C-130J-30s necessary for the requirement. Repeating this process iteratively results in the enumeration of all viable combinations of type and quantity. Figure 1 is a sample representation of this process.

3.1.2 Aircraft loading

After a set of alternative aircraft mixes are created, an iterative cargo loading algorithm ensures an equitable distribution of cargo items and verifies the viability of each alternative to handle the proposed requirements. This step is crucial because the weight of the payload affects the speed, fuel consumption, and number of stops necessary to complete the mission. Given *N* cargo items and *M* aircraft, the cargo items are sorted by weight (heaviest to lightest) and each cargo item is tested against each aircraft in each alternative.

The C-5B, C-5M, C-17A, and C-130J-30 use the standard 463L pallet, but can also accommodate larger cargo and rolling stock. If the cargo or rolling stock is too wide or tall to fit on the C-130J-30, it is called outsize cargo. The algorithm ensures that outsize cargo is only loaded on the C-5B, C-5M, or C-17A. The cargo items are loaded one by one onto all of the aircraft (checking for dimensionally outsized cargo, which cannot be loaded on C-130J-30s) and each aircraft's remaining available capacity is compared (both in terms of volume and weight) after the item is loaded. Since this must be applied to heterogeneous sets of aircraft, a percentage-based metric we called a "J-Rate" was adopted. The J-Rate calculates the used capacity of each aircraft, defined as the maximum of the consumed PPEs or weight capacity. After loading, the aircraft with the greatest remaining capacity available is selected and the cargo item is removed from the other aircraft. As shown in Fig. 2, this process is then repeated for all *N* cargo items until all items are assigned to the *M* specific aircraft types and respective quantities.

	C-5B	C-5M	C-17A	C-130J-30
Alternative 1	2	0	0	0
Alternative 2	1	1	0	0
Alternative 3	1	0	2	0
Alternative 4	1	0	1	3
Alternative 5	1	0	0	5
Alternative 6	0	2	0	0
Alternative 7	0	1	2	0
Alternative 8	0	1	1	3
Alternative 9	0	1	0	5
Alternative 10	0	0	3	0
Alternative 11	0	0	2	1
Alternative 12	0	0	1	5
Alternative 13	0	0	0	8

Fig. 1 Representative aircraft enumeration output (Maywald 2016)

3.1.3 Application of optimal routing and sortie metrics

The model benefits from previous modeling work by Reiman (2014) on routing algorithms and metrics. We use the nodal reduction technique in his prior research to quickly ascertain the optimal routing for each aircraft in an alternative based on that aircraft type's range constraints. Fuel consumption data is calculated by including his fuel regression equations for each aircraft type (see Eqs. 2–5). These equations were validated by the Air Force Research Laboratory and are currently used in their operational energy research. Equation 2 highlights how the fleet mix alternative can be optimized to minimize fuel consumption. Equations 3–5 provide a regression for the fuel consumption for the climb, cruise, and descent segments respectively. Based on Reiman (2014), the lowest R^2 for the three types of aircraft analyzed over climb, cruise, and descent segments were 0.98, 0.99 and 0.94, respectively.

$$\operatorname{argmin} \sum_{i=1}^{n}\sum_{j=1}^{o_i}\sum_{k=1}^{p_i}\sum_{l=1}^{q} \omega_{fc_{hijkl}} \forall h \in \text{Aircraft Mix Alternatives} \tag{2}$$

where

i	Aircraft mission design series (MDS)—type
n	Max number of aircraft MDS (4)
j	Aircraft tail
o_i	Max number of aircraft tails for that MDS
k	Sortie

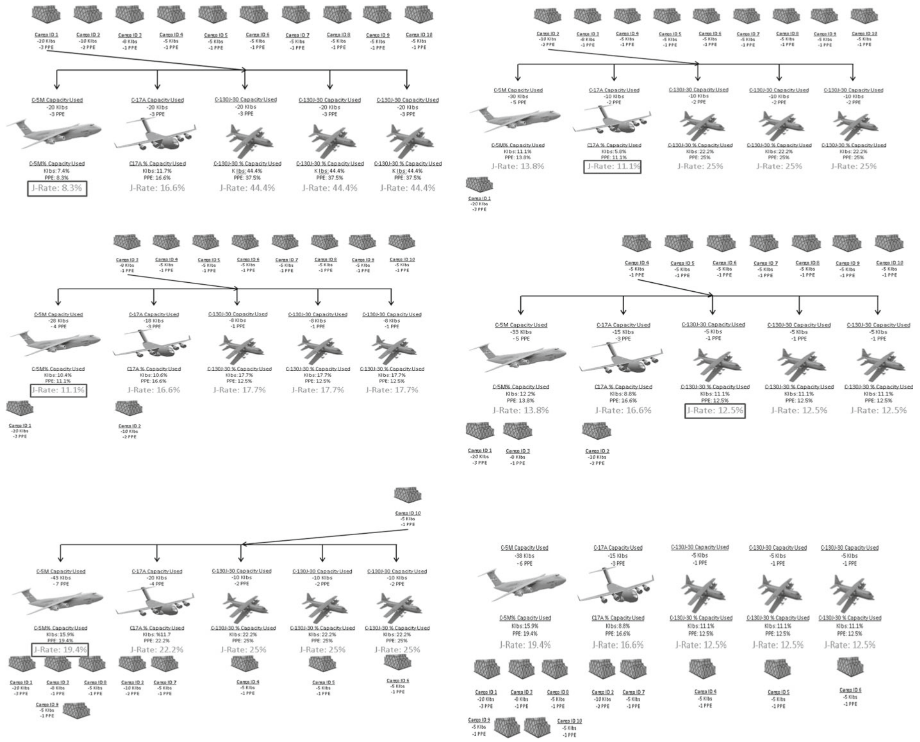

Fig. 2 Iterative cargo loading process (Maywald 2016)

p_i Max number of sorties for that MDS for maximum cargo throughput
l Fuel consumption component
q Max number of fuel consumption components (5)
$\omega_{fc_{hijk1}}$ Start, taxi and takeoff fuel weight (constant for each MDS)
$\omega_{fc_{hijk2}}$ Climb fuel weight
$\omega_{fc_{hijk3}}$ Cruise fuel weight
$\omega_{fc_{hijk4}}$ Descent fuel weight
$\omega_{fc_{hijk5}}$ Approach fuel weight (constant for each MDS)

$$\omega_{fc_{ijk2}} = \beta_0 + \beta_1\alpha + \beta_2\alpha^2 + \beta_3\alpha^3 + \beta_4\omega + \beta_5\omega^2 + \beta_6\omega^3 + 10^{-6}\beta_7\alpha^2\omega^3 + 10^{-6}\beta_8\alpha^2\omega^3 \tag{3}$$

where

$\omega_{fc_{hijk2}}$ Climb fuel weight in Klbs
β_i Regression betas on MDS-1-1 Climb Data, for i = 0, …, 8
α Altitude in thousands of feet
ω Aircraft gross weight in Klbs at Climb Start

$$\omega_{fc_{hijk3}} = -\frac{B}{3A} - \frac{1}{3A}\sqrt[3]{\frac{1}{2}\left[2B^3 - 9ABC + 27A^2D + \sqrt{\left(2B^3 - 9ABC + 27A^2D\right)^2 - 4\left(B^2 - 3AC\right)^3}\right]}$$
$$- \frac{1}{3A}\sqrt[3]{\frac{1}{2}\left[2B^3 - 9ABC + 27A^2D - \sqrt{\left(2B^3 - 9ABC + 27A^2D\right)^2 - 4(B^2 - 3AC)^3}\right]} \tag{4}$$

where (all weights in Klbs):

$\omega_{fc_{hijk3}}$ Cruise fuel weight
A $\frac{\beta_4}{3}$
B $\left(\frac{\beta_3}{2} + \beta_4\left(\omega_{op} + \omega_{frc} + \omega_{fah} + \omega_p\right) + \frac{\beta_5}{2}\alpha\right)$
C $\beta_0 + \beta_1\alpha + \beta_2\alpha^2 + \beta_3\left(\omega_{op} + \omega_{frc} + \omega_{fah} + \omega_p\right) + \beta_4\left(\omega_{op} + \omega_{frc} + \omega_{fah} + \omega_p\right)^2 + \beta_5\alpha\left(\omega_{op} + \omega_{frc} + \omega_{fah} + \omega_p\right)$

D $-\delta$
δ Distance in NMs
α Altitude in thousands of feet
β_{0-5} Regression Betas on MDS-1-1 Data
ω_{op} Operating weight
ω_{frc} Reserve/contingency fuel weight
ω_{fah} Alternate/holding fuel weight
ω_p Payload weight

$$\omega_{fc_{ijk4}} = \beta_0 + \beta_1\omega + \beta_2\omega^2 + \beta_3\alpha + \beta_4\alpha\omega \tag{5}$$

where

$\omega_{fc_{ijk4}}$ Descent fuel weight in Klbs
β_{0-3} Regression betas on MDS-1-1 data
α Altitude in thousands of feet
ω Aircraft gross weight in Klbs at descent start

3.2 Data collection

Data for this research were collected from two USAF systems, the Global Decision Support System (GDSS) and Global Air Transportation Execution System (GATES). By aggregating and cross-referencing data from GDSS and GATES, specific mission and cargo routing for the specified range of dates was determined and verified for use in our analysis.

GDSS is a command and control information system that provides unit-level and force-level mission planning, scheduling, and tracking of all USAF mobility airlift missions. The system is a vital tool that offers users information on the availability of aircrews, cargo aircraft, and ongoing missions (United States Air Force Force 2015b). The GDSS historical database includes important mission data that we included in our analysis including:

- Mission ID number
- Aircraft tail number
- Mission design series
- Mission type
- Departure/arrival times
- Departure/arrival locations
- Passengers
- Cargo payload

GATES is an information system that manages global air passenger and cargo data and is used primarily at aerial ports for tracking cargo movement worldwide. It is an important tool for providing in-transit visibility for cargo moving through the Defense Transportation System and provides specific cargo data useful for our analysis including:

- Mission ID number
- Aircraft tail number
- Mission design series
- Cargo ID number
- Cargo type
- Cargo weight
- Cargo dimensions
- Pallet position equivalents and volume
- Cargo departure/arrival times
- Cargo origin/destination

3.3 Design of the analysis

Once the ASM was created and data collected, the analysis had to be properly scoped. The GATES data contained cargo information for 2011 and 2012. In 2012, 271,000 cargo items were tracked originating and terminating at locations across the globe. In order to concentrate our emphasis on strategic airlift, the analysis was focused on four high-traffic intertheater city-pairs. These city-pairs and corresponding International Civil Aviation Organization codes were:

- Dover Air Force Base, Delaware (KDOV) to Ramstein Air Base, Germany (ETAR)
- Dover Air Force Base, Delaware (KDOV) to Rota Naval Station, Spain (LERT)
- Travis Air Force Base, California (KSUU) to Hickam Air Field, Hawaii (PHIK)
- Travis Air Force Base, California (KSUU) to Joint Base Elmendorf, Alaska (PAED)

The GATES data showed that cargo movement was highly seasonal and tended to peak in the summer months. Therefore, the analysis timeframe was reduced to 1 month of data (July 2012), which ensured that there was a relatively large amount of cargo moving from stateside to overseas. This allowed the ASM to derive unique alternative solutions. The approach used was to isolate the actual missions and individual cargo items moved in a single day between two of the selected city-pair locations (e.g., Dover to Ramstein). Using the GDSS database to verify the integrity of the GATES mission data, Table 3 summarizes the data used in the analysis.

3.4 Model assumptions

For the purposes of the analysis, several simplifying assumptions were made based on the data received and the limited scope of this study. First, many of the sorties analyzed carried passengers as well as cargo. For this analysis, we only considered cargo movement. Second, the ASM exclusively examined the USAF organic mobility fleet and therefore only considered the cargo transported by this fleet during the month analyzed. Third, GATES does not include information indicating if a cargo item is outsized (and therefore unable to be loaded to a C-130J-30); however, the data did indicate height, volume, and pallet type. Anything over 105 inches high was considered outsized per USAF instruction. It is important to note that no day required more than one outsized-cargo-capable airlifter. Fourth, all aircraft in this analysis reflected the originating US aerial port as the positioning and de-positioning location. Fifth, C-130J-30s must refuel in St. John’s International Airport, Canada in order to complete the Dover to Ramstein movements. This is reflected in the flight time and fuel consumption metrics; however, downtime at the enroute refueling location is not reflected in the model. Sixth, each day’s data were assessed as independent from other days. Seventh, many of the

Table 3 Consolidated cargo movement

	KDOV–ETAR				KDOV–LERT				KSUU–PHIK				KSUU–PAED			
	Sorties	Cargo IDs	PPE	Weight (Klbs)	Sorties	Cargo IDs	PPE	Weight (Klbs)	Sorties	Cargo IDs	PPE	Weight (Klbs)	Sorties	Cargo IDs	PPE	Weight (Klbs)
7/1	3	42	51.9	193	1	13	17.3	74.9								
7/2									1	21	27.1	42.5				
7/3																
7/4	1	11	17.3	43.7												
7/5																
7/6	2	43	48.4	189.5	2	24	32.3	92.5	1	16	16.2	21.2				
7/7	2	42	50.6	146	2	12	23.7	129.4	1	8	8	23.6				
7/8	2	20	20.2	112.5	1	14	15.4	42.3	1	8	14.3	93.4				
7/9	2	33	33	138.5	1	9	17.2	49.9					1	20	25.2	53.5
7/10													1	11	12.2	29.5
7/11					1	31	33.8	93.8								
7/12					1	3	9	100.2								
7/13					4	32	46.2	155.5								
7/14																
7/15	1	8	11.3	28.2	1	16	16.4	46.6	2	35	35.3	70.5	1	16	16	32.7
7/16									2	34	36	74.6				

Table 3 continued

	KDOV–ETAR				KDOV–LERT				KSUU–PHIK				KSUU–PAED			
	Sorties	Cargo IDs	PPE	Weight (Klbs)	Sorties	Cargo IDs	PPE	Weight (Klbs)	Sorties	Cargo IDs	PPE	Weight (Klbs)	Sorties	Cargo IDs	PPE	Weight (Klbs)
7/17	1	8	8	13.7					1	29	33.1	80.2				
7/18	1	8	8	27.1					1	6	13.8	72.8	1	18	18	36
7/19					1	10	17.9	23.2	1	12	18.8	38.2	2	18	21	41.7
7/20									1	14	16.4	39.4	1	31	34	77.1
7/21	1	11	12.8	33.4	1	15	28.9	124.2								
7/22													1	9	9	14.3
7/23					1	10	17.4	48.2	2	29	44.6	112.4	2	51	52	149.8
7/24					2	38	50.4	146.2	1	35	35	87.9				
7/25																
7/26					1	15	17.9	26.6								
7/27	2	16	22	105.6	1	8	17	27								
7/28	1	8	10	58.5	1	9	27	304	1	18	18	37.7				
7/29					1	16	18	74.8								
7/30	1	1	1	0.8												
7/31																
Total Sorties	20	251	294.5	1090.5	23	275	405.8	1559.3	16	265	316.6	794.4	10	174	187.4	434.6

C-5A/B/Cs used in the month of our analysis have since been modernized into C-5Ms, which are faster, have a greater range, and are more fuel efficient. Therefore, to avoid biasing our analysis we applied the C-5M metrics to all C-5A/B/Cs flown. Finally, we assumed that the required aircraft were available for this analysis. A limiting factor for mobility airlift planners is the limited number of aircraft available at any one time to meet demand.

4 Analysis

4.1 City-pair calculations

For illustrative purposes, we explain the analysis for one of the city-pairs (Dover to Ramstein). For the month of July 2012, cargo was moved on this city-pair 13 of 31 days. The GDSS/GATES data showed that 251 individual pieces of cargo accounting for 294.5 PPEs and 1,090,000 lb were moved on a total of 20 sorties. Of the 13 days analyzed, the model selected the actual alternative as the optimal minimum fuel alternative for just two of the days. For this city-pair, the C-17A, C-5B, and C-5M were each able to fly their sorties from KDOV to ETAR without stopping to refuel; however, our model required the C-130J-30 to stop for fuel in Canada (CYYT).

Table 4 lists the aggregate totals for the Dover to Ramstein city-pair for the entire month of July. To show both the savings as well as the flying hour increase, the changes are depicted as percentages of the actual costs and flying hours. That is, the fuel consumed using the ASM solution for 1 July is 54% of the fuel consumed on the actual mission. For the month of July there could have been significant savings with respect to fuel consumption (38%), AFTOC CPFH (29%), and logistics CPFH (33%); however, there is an increase in flying hours (55%).

4.2 City-pair totals

Table 5 lists the aggregate totals for all city-pairs for the entire month of July. Overall, there would be significant savings with respect to fuel consumption (27%), AFTOC CPFH (18%), and logistics CPFH (22%). Again, there is an increase in flying hours (84%).

4.3 ASM modification

The ASM selects an aircraft alternative based on a minimum fuel consumption objective. Because of the C-130J-30's low fuel consumption relative to the larger aircraft, there were several instances in which the ASM exchanged a larger aircraft sortie for multiple C-130J-30 sorties. In most of the scenarios the C-130J-30 alternative was the most fuel efficient and reduced the other cost factors as well. However, a closer examination of the other cost metrics showed that the ASM solution was not always the most cost-effective overall. Therefore, the ASM was modified to include an additional step where each scenario was examined individually and, if necessary, a total cost adjustment (TCA) was applied.

The TCA Value was calculated as the sum of the savings for fuel consumption, AFTOC CPFH, and logistics CPFH. If the TCA value was not positive indicating an overall savings, the modification allowed the model to revert to the actual aircraft mix selected. The TCA was applied to 4 days for the KDOV–LERT city-pair, 6 days for the KSUU–PHIK city-pair, and 1 day for the KSUU–PAED city-pair. As shown in Table 6, the savings for fuel

Table 4 Aggregate KDOV–ETAR totals

July		C-130J	C-17A	C-5A/B/C	C-5M	Fuel Consumption (%)	Flying Hours (%)	AFTOC CPFH (%)	LF CPFH (%)
KDOV–ETAR									
1	Actual		2	1		54	128	58	55
	ASM	2			1				
4	Actual		1			No change			
	ASM		1						
6	Actual		1		1	84	202	101	96
	ASM	2			1				
7	Actual		1	1		80	198	76	75
	ASM	2			1				
8	Actual		2			51	223	77	68
	ASM	3							
9	Actual		1		1	54	50	60	53
	ASM				1				
15	Actual		1			63	307	103	91
	ASM	2							
17	Actual			1		25	144	22	27
	ASM	1							
18	Actual		1			34	149	51	46
	ASM	1							
21	Actual		1			63	306	103	91
	ASM	2							
27	Actual		2			61	50	76	57
	ASM				1				
28	Actual		1			No change			
	ASM		1						
30	Actual		1			31	156	51	46
	ASM	1							
Totals	Actual	0	15	3	2	62	155	71	67
	ASM	16	2	0	5				

consumption is reduced by only 1%; however, the savings for AFTOC CPFH and logistics CPFH are increased by 5 and 6%, respectively. With the TCA the increase in flying hours is only 33%.

Since all alternatives are enumerated and because time, cost, and fuel consumed are metrics that are calculated in the ASM, we can easily sort on any parameter to better understand the decision space. The C-130J-30 ranks extremely high in fuel efficiency because of its size. Although a time penalty exists for using the C-130J-30, it is often insignificant. For example, flying 8 pallets on a C-130J-30 instead of a C-17A from Travis AFB in California to Hickam AFB in Hawaii will save the USAF over 100 Klbs of fuel and only increase delivery time by 2.2 h.

Table 5 Aggregate city-pair totals

		C-130J	C-17A	C-5A/B/C	C-5M	Fuel Consumption (%)	Flying Hours (%)	AFTOC CPFH (%)	LF CPFH (%)
All city pairs									
KDOV–ETAR	Actual	0	15	3	2	62	155	71	67
	ASM	16	2	0	5				
KDOV–LERT	Actual	0	16	7	0	79	174	77	76
	ASM	18	5	0	7				
KSUU–PHIK	Actual	0	12	0	4	82	237	108	98
	ASM	22	1	0	5				
KSUU–PAED	Actual	0	7	0	3	75	233	99	92
	ASM	14	0	0	3				
Totals	Actual	0	50	10	9	73	184	82	78
	ASM	70	8	0	20				

Table 6 Aggregate city-pair totals (with TCA)

		C-130J	C-17A	C-5A/B/C	C-5M	Fuel Consumption (%)	Flying Hours (%)	AFTOC CPFH (%)	LF CPFH (%)
All city pairs (with TCA)									
KDOV–ETAR	Actual	0	15	3	2	62	155	71	67
	ASM	16	2	0	5				
KDOV–LERT	Actual	0	16	7	0	80	110	70	70
	ASM	6	9	0	7				
KSUU–PHIK	Actual	0	12	0	4	85	102	92	85
	ASM	3	6	0	6				
KSUU–PAED	Actual	0	7	0	3	76	199	95	89
	ASM	11	1	0	3				
Totals	Actual	0	50	10	9	74	133	76	73
	ASM	36	18	0	21				

4.4 Summary

The results highlight several opportunities in which a smarter approach to aircraft selection can make a significant difference in fuel consumption and operating costs. The inclusion of the C-130J-30 and its effect in regards to overall efficiency is noteworthy. By supplementing the current strategic fleet with the smaller C-130J-30, flying hour costs are reduced and less fuel is consumed. However, it was discovered that the ASM's strict minimum-fuel objective approach selected alternatives that saved fuel, but were not always cost-effective. By adding the additional total cost adjustment step to the model, aircraft alternatives were enumerated that revealed substantial opportunities for cost savings.

5 Conclusions, limitations and future research

An effective military air transportation system is vital to the concept of rapid global mobility, which is a key part of implementing US military strategy. Conceptualizing the rift between tactical and strategic airlift is a necessary part of planning in the hub-and-spoke construct; however, that does not mean airlift assets must be categorized in the same manner. The improvements in speed, range, and cargo capacity give the C-130J-30 parity to a degree with the USAF's larger mobility aircraft. Thus, its merits as an intertheater airlifter should be analyzed.

The ASM revealed many opportunities in which a holistic modeling approach to aircraft selection can be effective in selecting alternatives that could have reduced overall fuel consumption. While using total cost for the objective function may be desired, it is problematic in that it relies on the cost per flying hour technique. Given two of the same type of aircraft, if one aircraft has a higher gross weight, it must fly faster in order to optimize fuel efficiency. At the increased speed the cost per flying hour technique would suggest that the total cost is less. However, all other things being equal, heavier aircraft burn more fuel. It is for this reason, that using fuel consumption was selected by the research team.

The estimated one-way Logistic Factor based total savings including the TCA for the four city-pairs could have been as high as $1.17M for the month of July 2012. The actual cost and the model cost were calculated using the AFTOC cost per flying hour, the Logistic Factor cost per flying hour, and the fuel cost. The flying hours and fuel consumed were determined using aircraft performance models developed by Reiman (2014). The AFTOC and Logistic Factor alternative cost was the CPFH multiplied by the flying hours round trip. The fuel alternative cost was $2.95 per gallon multiplied by the gallons of fuel consumed round trip. The round trip savings using AFTOC, Logistics Factor and Fuel Cost respectively for the four city pairs over the month when optimizing on fuel were $0.86M, $2.34M and $1.89M. The round trip savings using AFTOC, Logistics Factor and Fuel Cost respectively for the four city pairs over the month when adjusting for Total Cost were $1.57M, $3.18M and $1.80M.

The model also provided evidence of the viability of the C-130J-30 in the strategic airlift mix. Going forward, the ASM offers a cost–benefit analysis tool for aircraft basing alternatives and encourages a conceptual shift in the tactical/strategic categorization of airlift assets. The main advantage of a holistic approach is its ability to more closely tailor aircraft capacity to a variable demand resulting in less wasted capacity and greater load factors. These findings challenge the private and public sector hub-and-spoke model, which has remained static despite vast improvements in aircraft technology.

The ASM can be a useful tool for analysis, but has notable limitations. The assumption of aircraft availability does not reflect the reality that airlift planners face. The mobility mission is extremely dynamic, with aircraft locations, crew availability, and resource demand changing by the hour. Training hours and crew proficiency must also be taken into account.

The insights provided by the ASM create multiple areas for future research. First, the use of the ASM could be extended to additional city-pairs. Next, as demonstrated by the use of the total cost adjustment, the ASM is easily modified. A study of how airlift planners choose objective functions, whether it be fuel, cost, or time. Finally, the inclusion of the C-130J-30 in the strategic airlift mix would require analysis of basing alternatives as well as the effect on aircraft lifespan for the entire fleet.

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